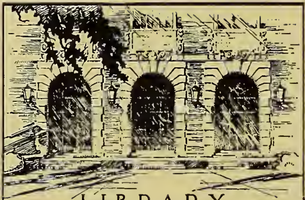

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ELECTROMAGNETIC FIELDS IN RECTANGULAR SLOTS

by

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This manuscript would be incomplete without acknowiedging G.C. Mochel and G.C. Barryman for performing the calculations and taking most of the data.

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ILLUSTRATIONS

ILLUSTRATIONS (CONTINUED)

ABSTRACT

This investigation concerns the determination of the distributions of electromagnetic field in long, narrow, rectangular slots in a conducting plane illuminated by a normally incident, uniform plane wave. Measured aperture distributions in slots from three to four wavelengths long are found to closely approximate distributions calculated by use of the reaction concept.

1. INTRODUCTION

The advancement of microwave techniques has stimulated interest in the diffraction of electromagnetic fields caused by apertures in infinite screens. The aperture field is of interest since the fields everywhere can be expressed in terms of the field in the aperture. Levine and Schwinger[1] have approximated the fields diffracted by an aperture by using variational principles. Andrews[2] and others[3] have been concerned with diffraction at short distances caused by circular apertures in an infinite screen. In a set of unpublished notes, V.H. Rumsey indicates how the reaction concept may be used to approximately calculate the fields in the aperture. In his notes Professor Rumsey considers the example of a long, narrow, rectangular slot in an infinite screen when the screen is illuminated by a normally incident, uniform plane wave.

This investigation concerns the actual, approximate calculation of the aperture fields in such a slot as Rumsey considers by use of the reaction concept. Since the calculations indicate peculiar humps in the magnitude of electric field as the test source is moved along the slot, an experimental verification is also considered here.

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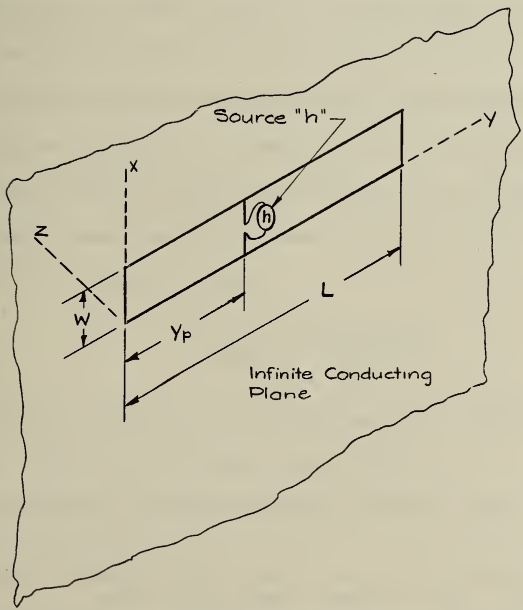
1. See numbered reference in the bibliography. All such numbers throughout this manuscript refer to numbers in the bibliography.

2. CALCULATION OF APERTURE DISTRIBUTIONS

A general method for the application of the reaction concept[4] to an approximate calculation of the field distribution in an aperture has been developed in a set of unpublished notes by Prof. V.H. Rumsey. In these notes this general method is applied to the calculation of the field distribution in a long, narrow slot in an infinite, conducting plane excited by a normally incident, uniform plane wave. The source and slot arrangement are shown in Fig. 1.



g > source "g"

FIGURE 1 SOURCE ARRANGEMENT FOR CALCULATION OF THE FIELD IN A LONG, NARROW SLOT

In the absence of the conducting plane the source "g" generates a uniform plane wave normal to the x-y plane with its electric field in the x direction. The slot width W is assumed small enough that the electric field in the slot is entirely in the x direction and does not vary with x. The source "h" is a test source located at an arbitrary point, y_p, along the slot. This test source consists of a unit current source connected to an infinitesimal dipole which is parallel to the x-axis. With this source arrangement the reaction* between sources "g" and "h" is equal to the x component of electric field at y_p due to the source "g".

A direct evaluation of $\langle g,h\rangle$ is not possible; however, the reaction concept provides a means of obtaining an approximate value for $\langle g\ h\rangle$. Let the source "a" represent an assumed distribution of magnetic currents over the surface of the slot which produces approximately the same fields in the slot as are produced by source "g"; let the source "b" represent an assumed distribution of magnetic currents over the surface of the slot which produces approximately the same fields in the slot as are produced by source "h". Then the formula

$$\langle g,h\rangle \simeq \frac{\langle a,h\rangle \langle b,g\rangle}{\langle a,b\rangle} \tag{1}$$

gives a value for $\langle g,h\rangle$ which is stationary for variations of the assumed sources "a" and "b" about their correct values.

The assumptions that the tangential electric field in

---

*The reaction between two sources "g" and "h" is defined as

$$\langle g,h\rangle = \iiint_V \left[\underline{E}(h) \cdot d\underline{J}(g) - \underline{H}(h) \cdot d\underline{K}(g)\right]$$

where $\underline{E}(h)$ and $\underline{H}(h)$ are the electric and magnetic fields generated by source "h", $d\underline{J}(g)$ and $d\underline{K}(g)$ are the volume distributions of electric and magnetic current of the source "g" and the volume V contains source "h".

The reciprocity theorem gives $\langle g,h\rangle = \langle h,g\rangle$ for isotropic media, provided sources "g" and "h" are contained in a finite volume.

the slot is in the x-direction and that source "g" is a uniform plane wave with $E_y(g) = 0 = E_z(g)$, $H_y(g) = 1$ gives for $\langle b,g\rangle$

$$\langle b,g\rangle = -2\int_o^L \int_o^W E_x(b)\ dx\ dy \tag{2}$$

where $E_x(b)$ is the electric field along the slot due to the assumed source "b". Thus $E_x(b)$ is an assumed value for the electric field produced in the slot by a unit current source located at y_p. A reasonable assumption for $E_x(b)$ is to assume it proportional to the voltage produced along a transmission line of length L excited by a unit current source at y_p and shorted at $y = 0$ and $y = L$. This assumption gives

$$E_x(b) \sim \frac{\sin\beta(y_p - L)\ \sin\beta\ y}{\beta\ \sin\ \beta L} \quad 0 \leq y \leq y_p$$

$$\sim \frac{\sin\beta\ y_p\ \sin\beta\ (y-L)}{\beta\ \sin\ \beta L} \quad y_p \leq y \leq L \tag{3}$$

where $\beta^2 = \omega^2 \mu\ \epsilon$. Substitution of E_x (b) from Eq. 3 into Eq. 2 gives

$$\langle b,g\rangle \sim \cos\ \beta(y_p - \frac{L}{2}) - \cos\ \frac{\beta L}{2}\ . \tag{4}$$

Since $\langle b,g\rangle$ and $\langle a,h\rangle$ should both represent the voltage in the slot due to source "g", it is consistent to assume source "a" so that $\langle a,h\rangle = \langle b,g\rangle$. This condition forces source "a" to be such that $E_x(a) \sim \langle b,g\rangle$, where $E_x(a)$ is the field produced in the slot by source "a". These assumptions for sources "a" and "b" give, for $\langle a,b\rangle$,

$$\langle a,b\rangle \sim \int_o^L \int_o^L \int_o^W \int_o^W g(y)\ f(y')\ [\beta^2 + \frac{\partial^2}{\partial y^2}]\ \frac{e^{-j\beta|r|}}{|r|}\ dx\ dx'\ dy\ dy' \tag{5}$$

where

$$f(y) = E_x(a)$$

$$g(y) = E_x(b)$$

$$r^2 = (x-x')^2 + (y-y')^2$$

While Eq. 5 for $<a,b>$ may be simplified, no method could be found to evaluate it without using, in part, numerical methods. The expression was first reduced to a double integral, and the final integrations were made using the digital computer, ILLIAC. For all numerical calculations a slot width of $\beta W = 0.2$ ($W = 0.0319\lambda$) was used. This slot width was chosen as it allowed a better than 1% accuracy in the numerical calculations and still required a reasonable computation time. Approximate field distributions were calculated for slot lengths from $\beta W = 6$ ($L = 0.955\lambda$) to $\beta W = 75$ ($L = 11.95\lambda$).

In Figs. 2 through 6 curves are plotted showing $|<g,h>|$ as calculated from Eq. 1 and $|<b,g>|$ as calculated from Eq. 4. It will be noted that for the 0.955λ slot the assumed distribution $|<b,g>|$ and the next approximation from the stationary formula of Eq. 1 show very good agreement. Therefore, for this slot length it seems likely that the assumed distribution is a good one. For the longer slots the curves $|<g,h>|$ and $|<b,g>|$ have the same form where the field is large, but they do not compare where the field is small. It will be noted that the assumed field along the slot is zero at several points and that $|<g,h>|$ from Eq. 1 will be zero at the same points. Thus, it is not expected that $|<g,h>|$ should accurately represent the field in the slot near points where the field is a minumum.

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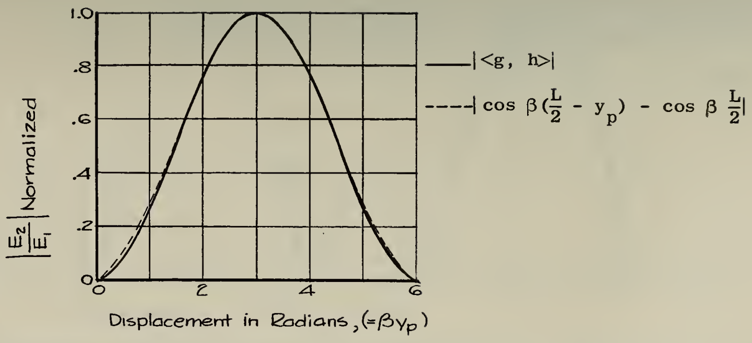


FIGURE 2 CALCULATED APPROXIMATE AMPLITUDE DISTRIBUTION IN A 0.955λ SLOT ($\beta L = 6$)

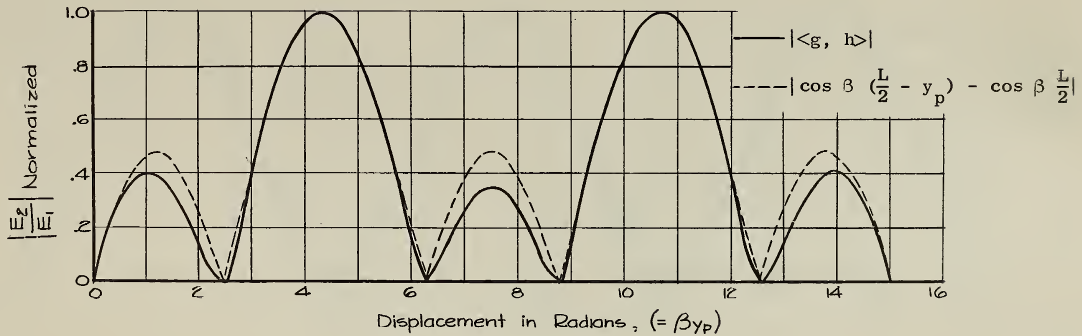


FIGURE 3 CALCULATED APPROXIMATE AMPLITUDE DISTRIBUTION IN A 2.39λ SLOT ($\beta L = 15$)

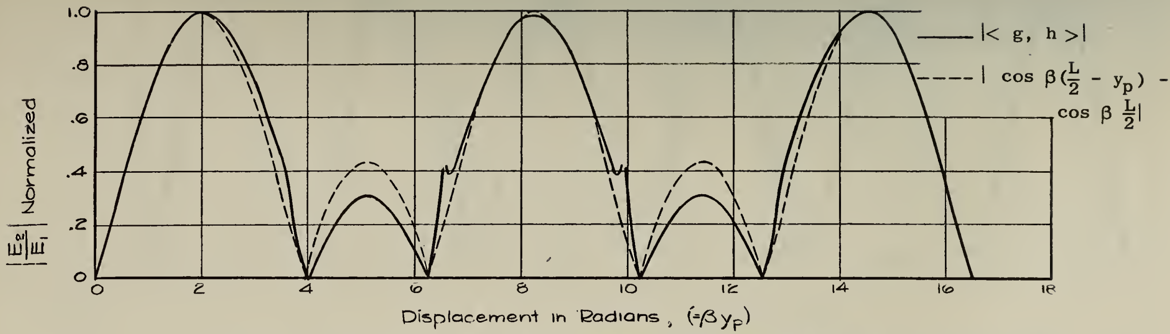


FIGURE 4 CALCULATED APPROXIMATE AMPLITUDE DISTRIBUTION IN A 2.63λ SLOT ($\beta L = 16.5$)

FIGURE 5 CALCULATED APPROXIMATE AMPLITUDE DISTRIBUTION IN A 2.87λ SLOT ($\beta L = 18$)

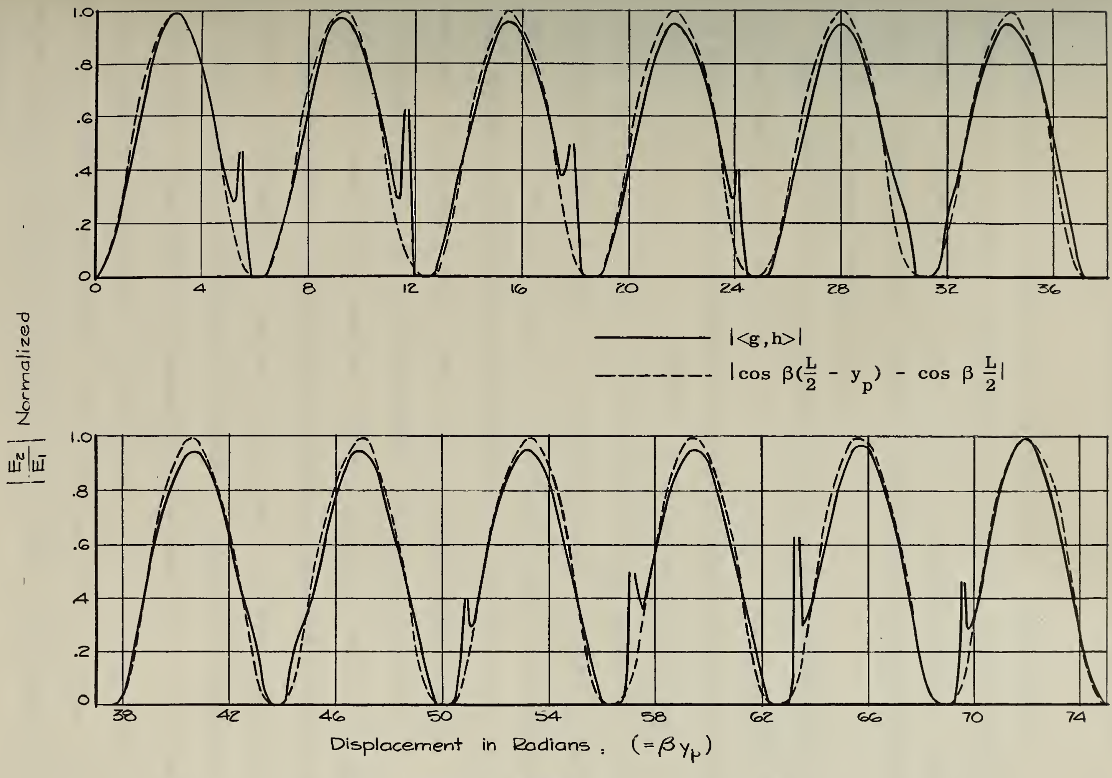


FIGURE 6 CALCULATED APPROXIMATE AMPLITUDE DISTRIBUTION IN AN 11.95 λ SLOT ($\beta L = 75$)

3. EXPERIMENTAL DETERMINATION OF APERTURE DISTRIBUTIONS

The measurement of the field distribution in a long, narrow, rectangular slot presents, among others, the problems of where and how to probe the field, where to put associated measuring apparatus, how to achieve a uniform plane wave, and how to approximate an infinitely thin, infinitely extending, conducting plane.

Measurement of the aperture distribution is accomplished here by using the experimental setup of Fig. 7. An image plane is place perpendicular to the plane of the slot and bisecting the narrow dimension of the slot. The effect of such a plane is to reproduce below its surface the image of what is on top of the plane in the same manner as the image of an object is reproduced behind a mirror. The advantage of this system is that the space below the image plane may now be utilized to house the probe and associated measuring apparatus, thus shielding it from the field to be measured. The image plane, as well as the aperture plane, must be terminated in such a way as to approximate the system of infinite dimensions. Edge effects created by these terminations must be minimized.

An approximation of a uniform plane wave is launched along the image plane by a horn located at one end of the plane. A sliding section of the image plane is used beneath the aperture. This section contains a small hole through which the measuring probe penetrates. The probe can then be located at any point in the aperture. It is not permissible to move this probe in another slot, cut in the image plane, because this second slot would disturb the currents on the image plane caused by the plane wave.

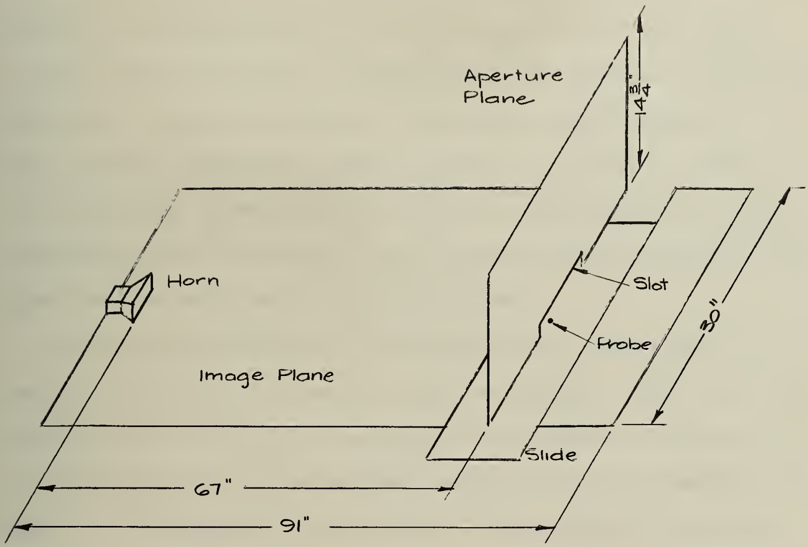


FIGURE 7 IMAGE AND APERTURE PLANES

Since a frequency of 9600 mc or a wavelength of 3.125 cm is used throughout this investigation, the dimensions shown in Fig. 7 result in an aperture plane of 24.4λ by 12λ and an image plane of 74λ by 24.4λ. The distance from the horn to the aperture is 53.4λ. The slots are 0.040λ high, resulting in a height of 0.080λ in the equivalent free space case. The material from which the slots are constructed is 0.032 in. or 0.026λ thick copper. Such a thickness is necessary to maintain a rigid aperture plane under the strain of the sliding section. Since good electrical contact between the aperture plane and the image plane must be maintained, at least at the ends of the slots, the aperture plane

is tapered slightly at the bottom edge in such a way that the lowest portion of the aperture plane is at the edges of slot; thus contact at these points is insured. To facilitate construction and installation of the slots the aperture plane is fabricated in two sections; the upper section is permanently mounted, and the lower section consists of a 3 in. strip, in which the slot is cut. These strips may be easily constructed to the desired slot length and then rigidly fastened to the upper part for measurement of the distribution.

Two different probes were used for mechanical reasons, one for amplitude measurements and one for phase measurements. The hole in the sliding section is 0.085 in. in diameter for the amplitude probe, and it is reduced to 0.058 in. for the phase probe by means of a bushing. The diameter of the amplitude probe measures 0.032 in. and the diameter of the phase probe is 0.021 in.

Suppression of the edge effect, caused by the finite size of the image plane, is achieved by installing aluminum rolls of nine inch radius at the edges of the image plane. These rolls give a gradual transition from the metallic plane to the surrounding free space. The edges of the aperture plane are terminated by pieces of cardboard saturated with Aquadag; thus the radiation at these edges is absorbed. Reflections from within the laboratory are reduced by means of panels of absorbing material placed in front of the reflecting objects.

The arrangement of equipment for measuring the amplitude distribution is shown in Fig. 8. The signal at the point where the probe is located is demodulated by a calibrated crystal, and the strength is indicated on the standing wave amplifier.

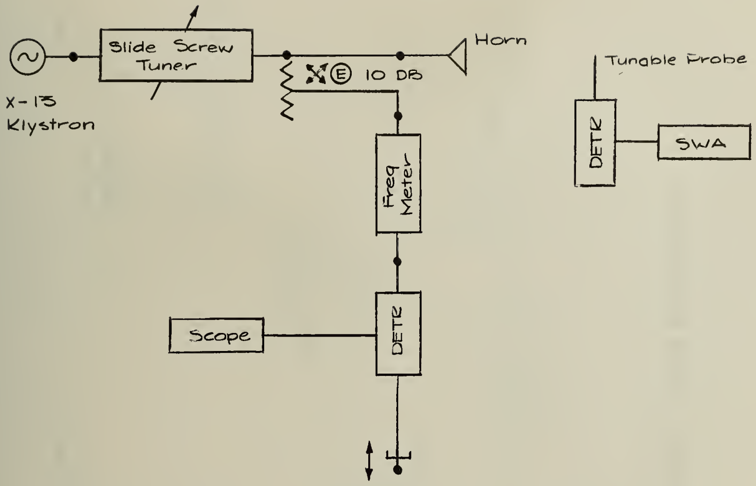


FIGURE 8 EQUIPMENT FOR MEASURING AMPLITUDE DISTRIBUTION (Not to Scale)

Phase measurements are performed with equipment arranged as in Fig. 9. A small portion of the klystron power is tapped off to provide a reference signal. The probe is excited by the field in the slot. The probe in turn excites the waveguide through a slotted waveguide section. This signal is then mixed with the reference signal in a directional coupler and detected by a crystal and standing wave amplifier. The amplitude and phase of the reference signal can be changed by means of adjusting the calibrated phase shifter and calibrated attenuator. When the reference signal and the signal from the slot are of the same magnitude but 180° out of phase at the detector, a null is read on the

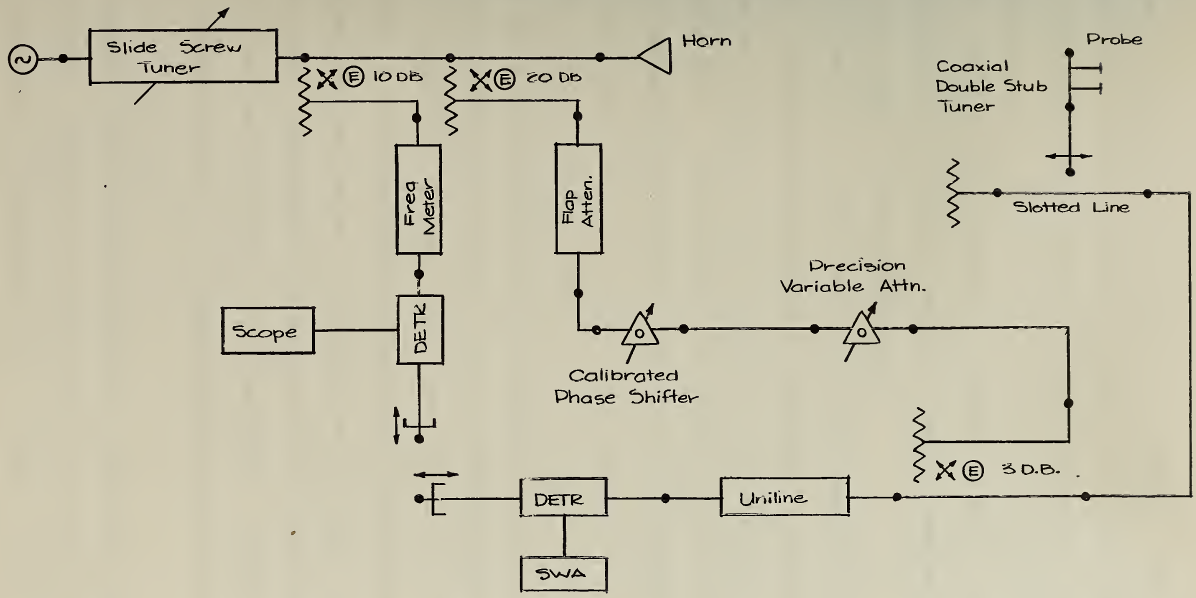


FIGURE 9 EQUIPMENT FOR MEASURING PHASE DISTRIBUTION
(Not to Scale)

standing wave amplifier. The change of the reference signal necessary to bring about this null indicates the phase at the probe position in the slot. Amplitude is not measured in this way because with a rigid probe running from the slot to the slotted section it is too difficult to maintain constant probe penetrations as probe position is varied. These varying penetrations change the amplitude readings considerably but have very little effect on phase determination.

Patterns of the incident wave were taken without the aperture plane present. To shield the probe from the rear edge, or the edge of the image plane without the horn, it was necessary to mount a vertical plane $1/4\lambda$ behind the probe. Since the angle of incidence was, for practical purposes, normal, the patterns obtained were those of the wave propagated by the horn on the image plane in the absence of the aperture plane. The primary amplitude pattern is shown in Fig. 10. It is seen that this varies about 1/2 db over a range extending for two wavelengths to each side of the center. The primary phase pattern, shown in Fig. 11, indicates that the phase varies by less than 13° over the same range. Since this range approximates a plane wave, it is within this range that the slots are placed, and measurements are carried out. The primary patterns shown in Figs. 10 and 11 are typical, and repeated patterns have the same characteristics. Amplitude patterns are within 0.1 db of each other, and phase patterns have a maximum deviation of 6° between various sets of data but an average deviation of only about 1°.

Amplitude distributions for various slot heights were taken, and, by comparing Figs. 12 and 20, it is seen that the variation in height causes little variation in the amplitude pattern. Figures 13 and 20 show

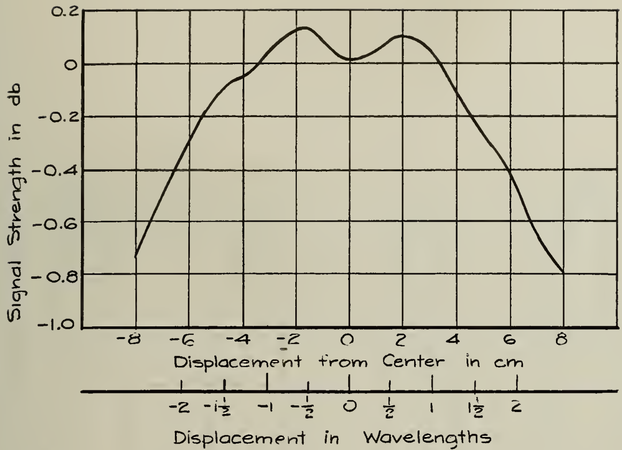


FIGURE 10 TYPICAL AMPLITUDE PATTERN OF INCIDENT WAVE

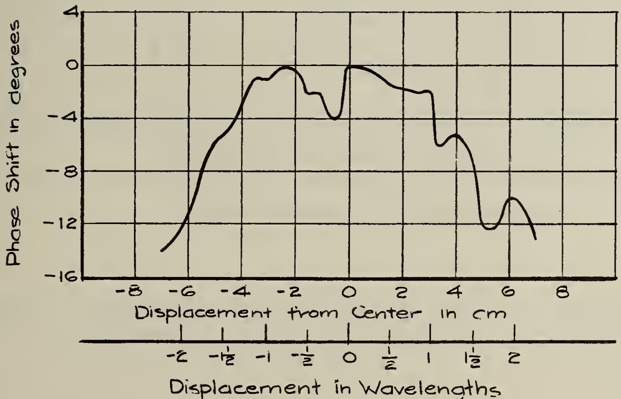


FIGURE 11 TYPICAL PHASE PATTERN OF INCIDENT WAVE

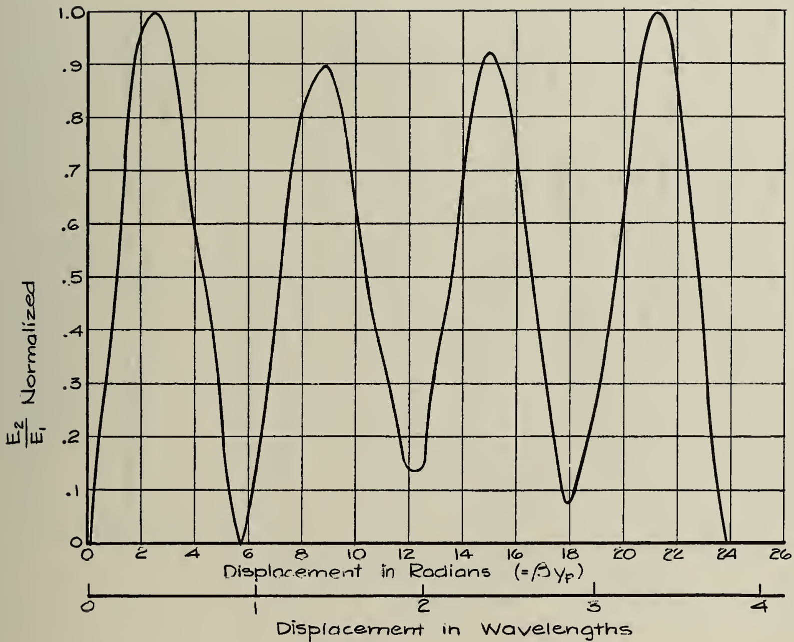


FIGURE 12 EXPERIMENTAL AMPLITUDE DISTRIBUTION OF A 3.75λ SLOT
Slot Height: 0.053λ; Probe Penetration: .020 in.

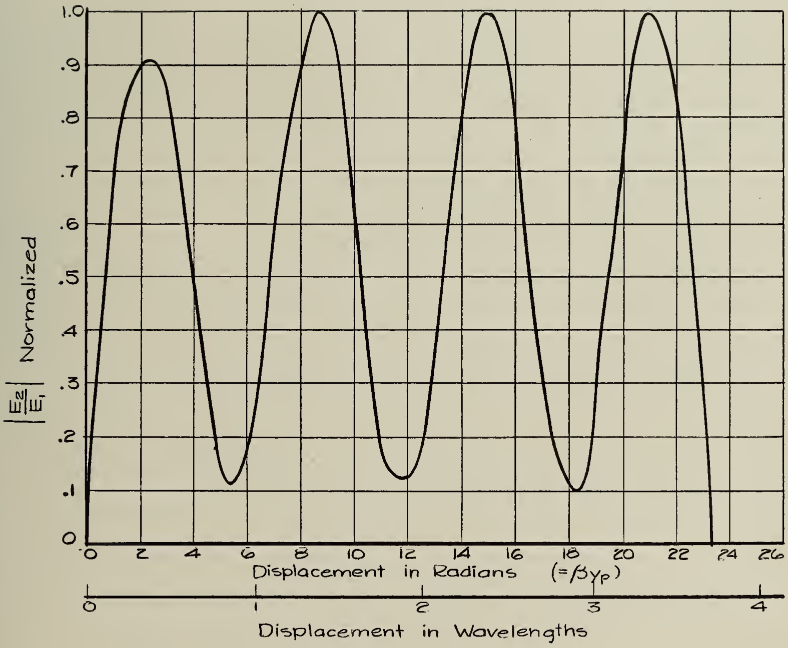


FIGURE 13 EXPERIMENTAL AMPLITUDE DISTRIBUTION OF A 3.75λ SLOT
Slot Height: .040λ; Probe Penetration: .030 in.

the patterns for probe depths of 0.020 in. and 0.030 in. for the same aperture. A study of these patterns shows that only small variations are experienced by changes in probe penetration.

4. PRESENTATION OF EXPERIMENTAL RESULTS AND COMPARISON WITH THEORETICAL RESULTS

In order to show how the field distribution varies as the length of the aperture is increased, the experimental amplitude and phase patterns of slots of three to four wavelengths, of height 0.040λ, increasing in length by $1/8\lambda$ steps, are shown in Figs. 14 through 22. For mechanical reasons the height, $W = 0.040\lambda$, was about the smallest which could be measured with a suitable degree of accuracy in this frequency range. It is felt that a decrease in W would not change the field distribution appreciably.

Since comparison of theoretical and experimental curves is desirable, the theoretical amplitude and phase distributions for slots of height $W = 0.031\lambda$ and of corresponding length are also indicated on most of the same graphs.

Because the absolute phase at a certain probe position in the aperture with respect to that of the plane wave would be difficult to determine experimentally, the phase at the center of the slot is always chosen to read 0^o. In order to compare the theoretical and experimental phase patterns, the theoretical patterns were also shifted in such a way as to read 0^o phase shift in the center of the aperture. It is known, however, that the absolute phase at the ends of the slot must be zero. Establishment of an experimental phase reference at these points is impossible, however, because the field is zero.

Study of the experimental amplitude patterns shows a reluctance to

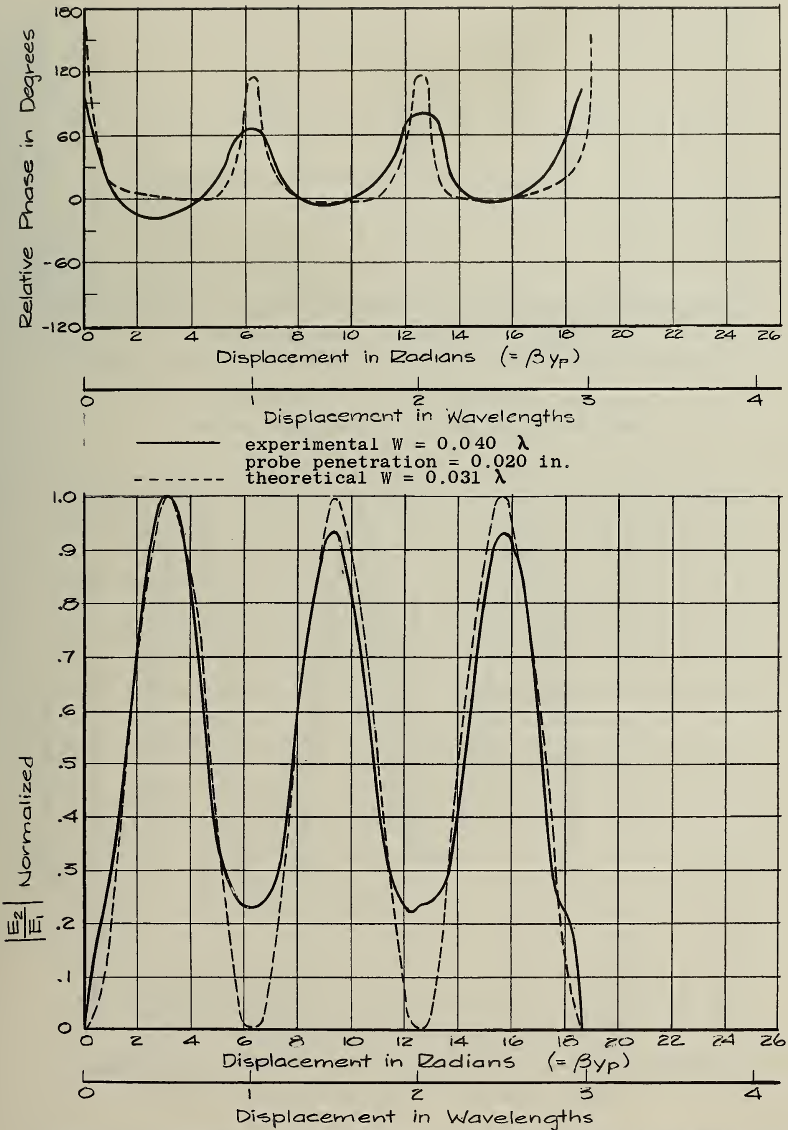
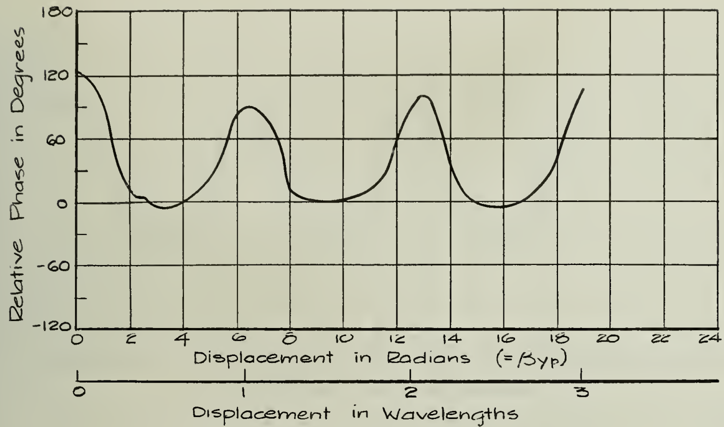


FIGURE 14 PHASE AND AMPLITUDE DISTRIBUTION OF A THREE WAVELENGTH SLOT



probe penetration = 0.020 in.; W = 0.040λ

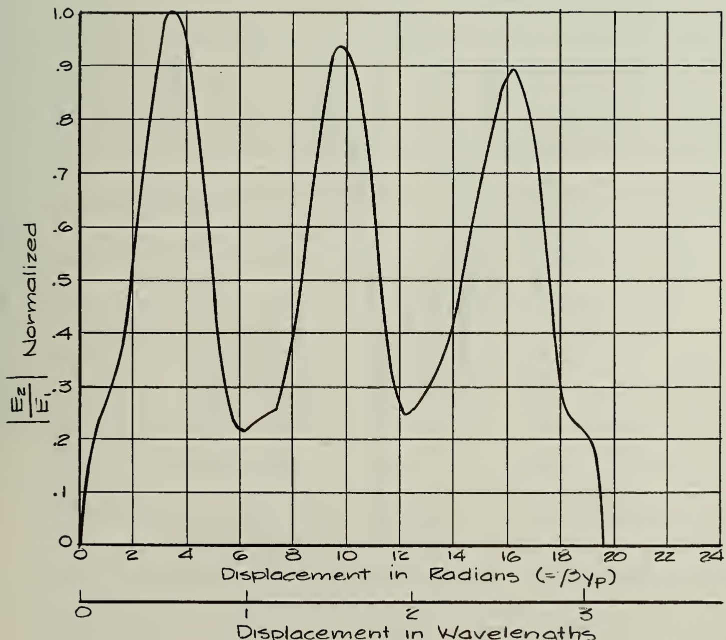


FIGURE 15 EXPERIMENTAL PHASE AND AMPLITUDE DISTRIBUTION OF A 3.125 WAVELENGTH SLOT

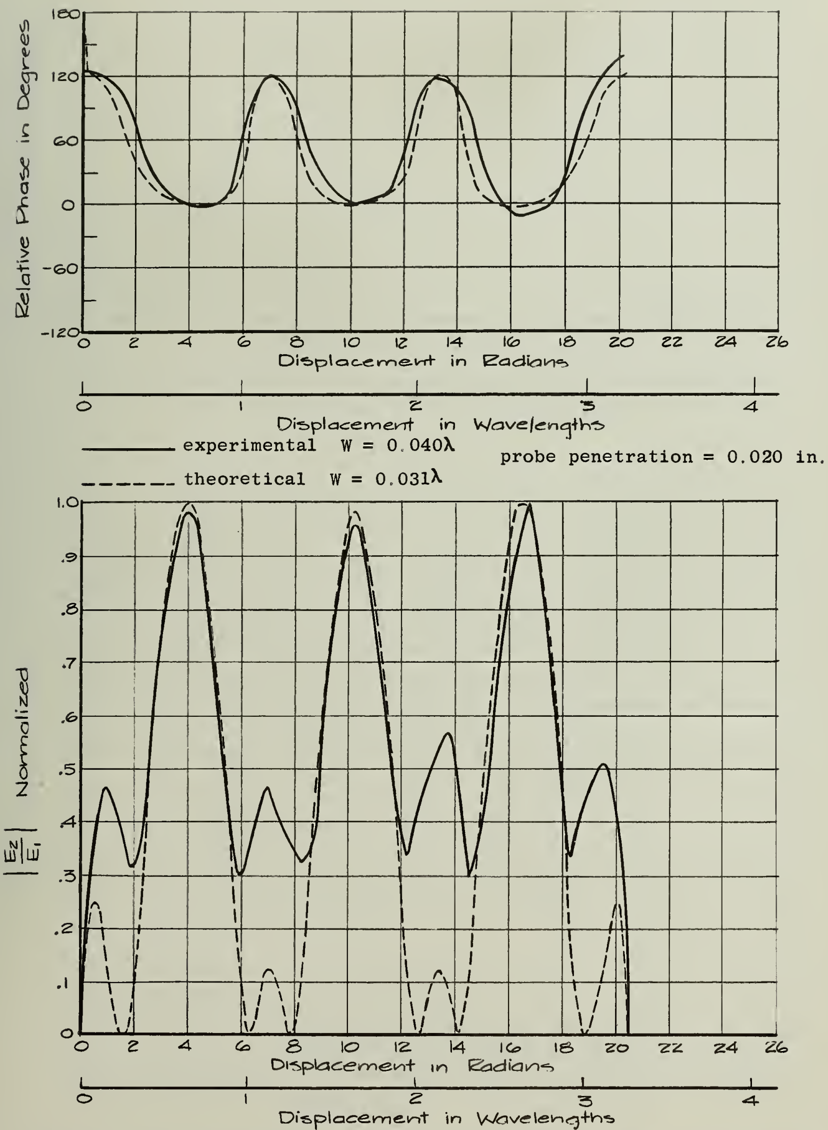


FIGURE 16 PHASE AND AMPLITUDE DISTRIBUTION OF A 3.25 WAVELENGTH SLOT

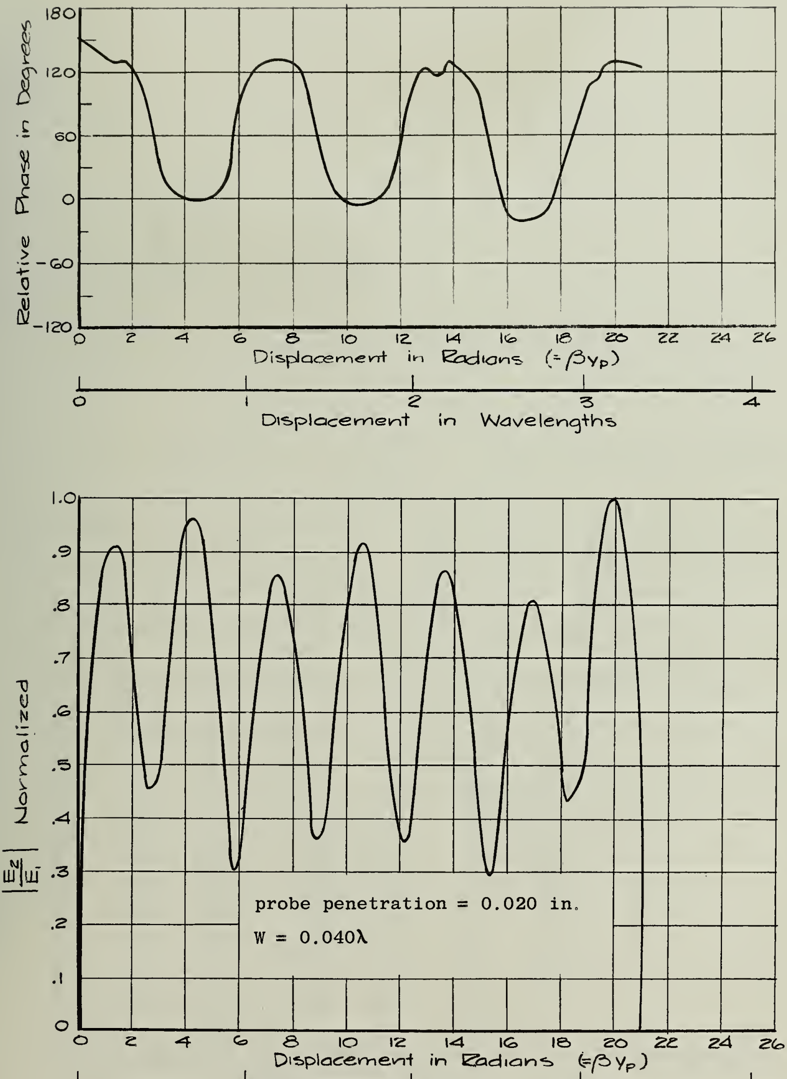


FIGURE 17 EXPERIMENTAL PHASE AND AMPLITUDE DISTRIBUTION OF A 3.375 WAVELENGTH SLOT

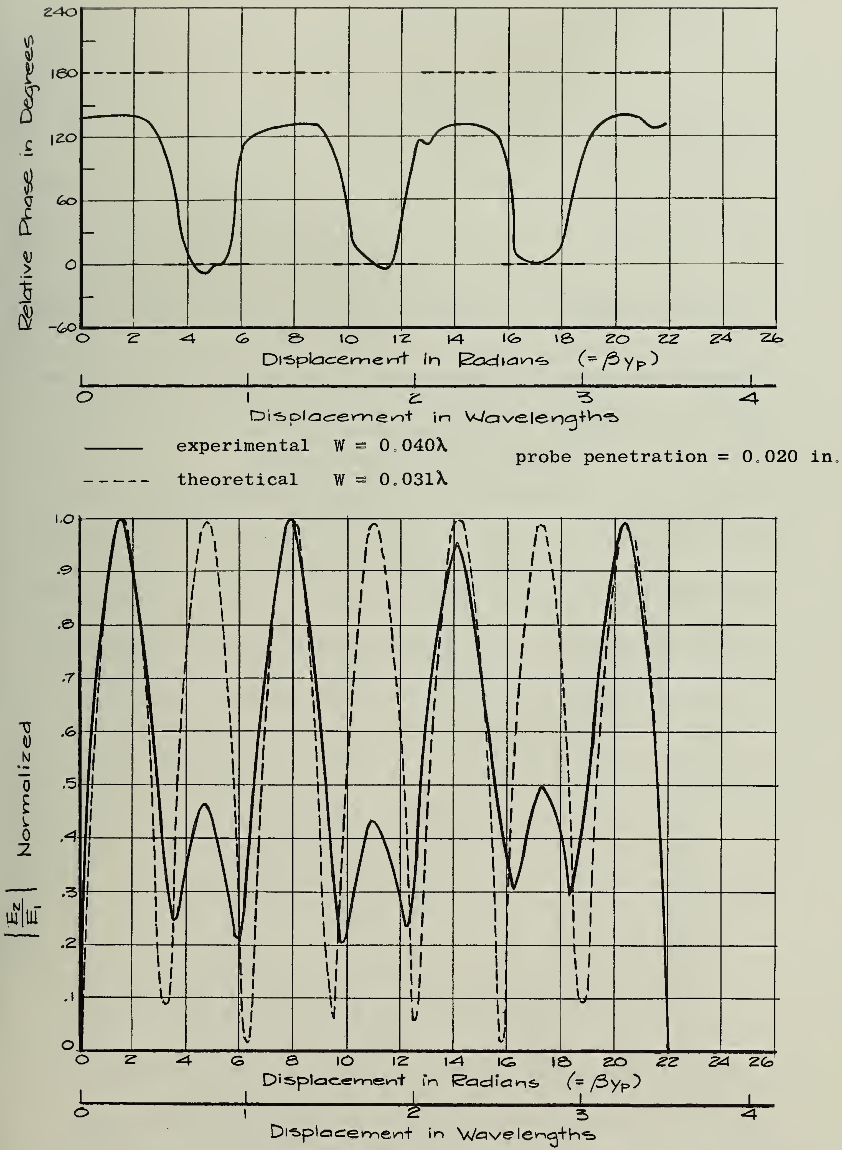
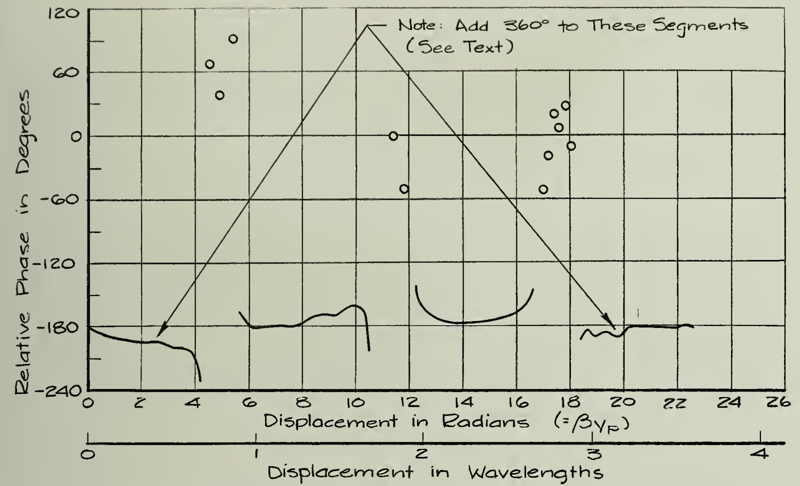


FIGURE 18 PHASE AND AMPLITUDE DISTRIBUTION OF A 3.5 WAVELENGTH SLOT



probe penetration = 0.020 in. W = 0.040λ

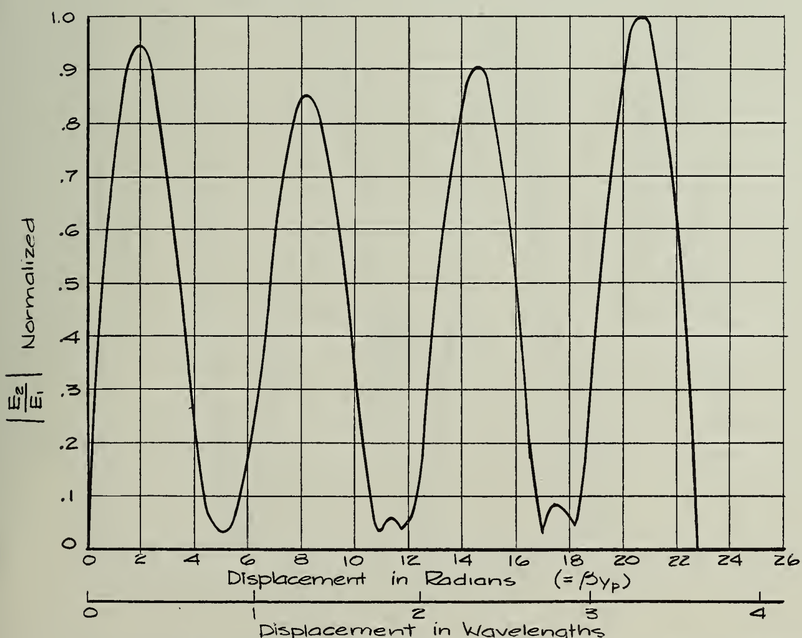


FIGURE 19 EXPERIMENTAL PHASE AND AMPLITUDE DISTRIBUTION OF A 3.625 WAVELENGTH SLOT (NOTE INDICATED PHASE DISPLACEMENT).

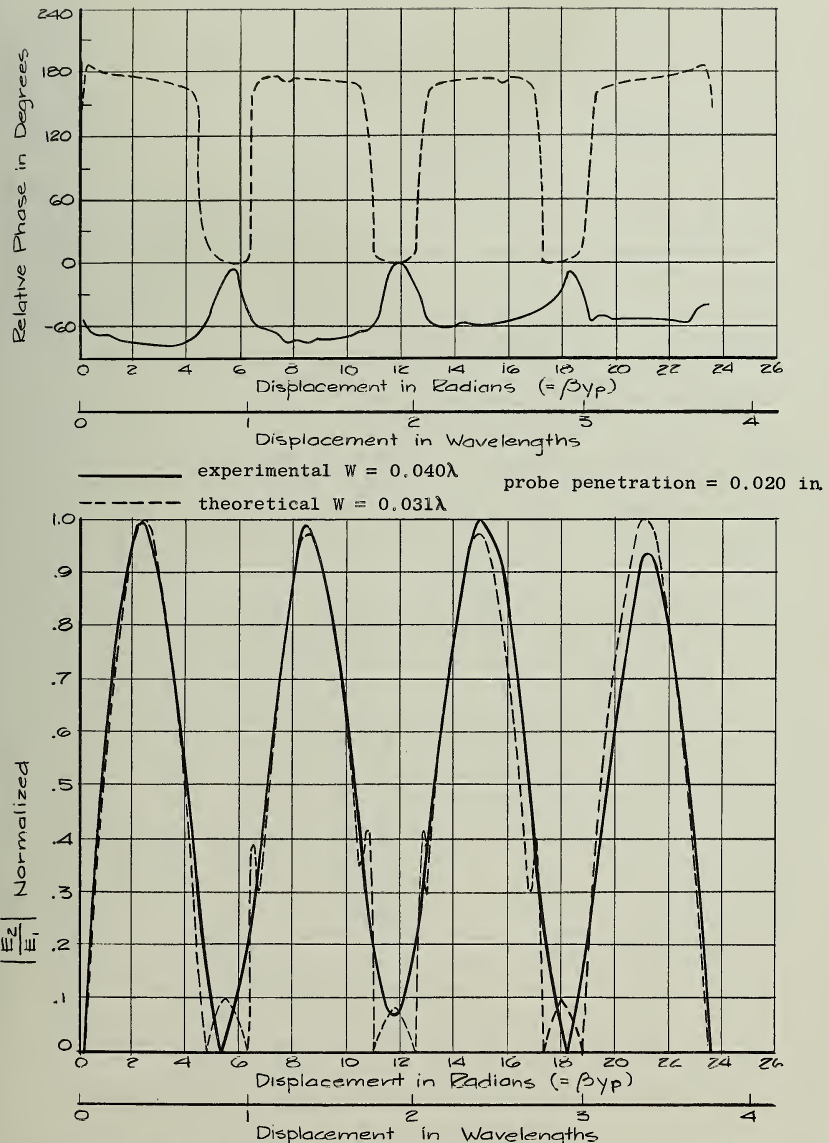


FIGURE 20 PHASE AND AMPLITUDE DISTRIBUTION OF A 3.75 WAVELENGTH SLOT

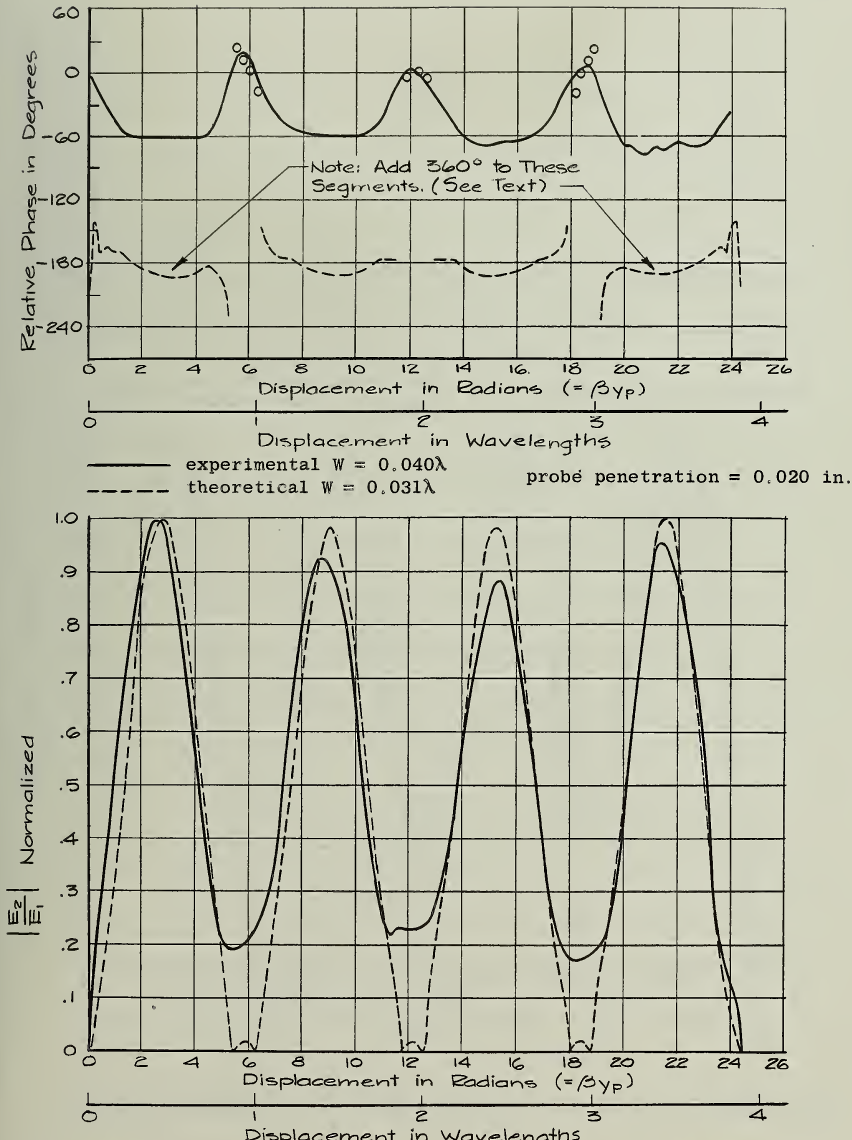


FIGURE 21 PHASE AND AMPLITUDE DISTRIBUTION OF A 3.875 WAVELENGTH SLOT (NOTE INDICATED THEORETICAL PHASE DISPLACEMENT)

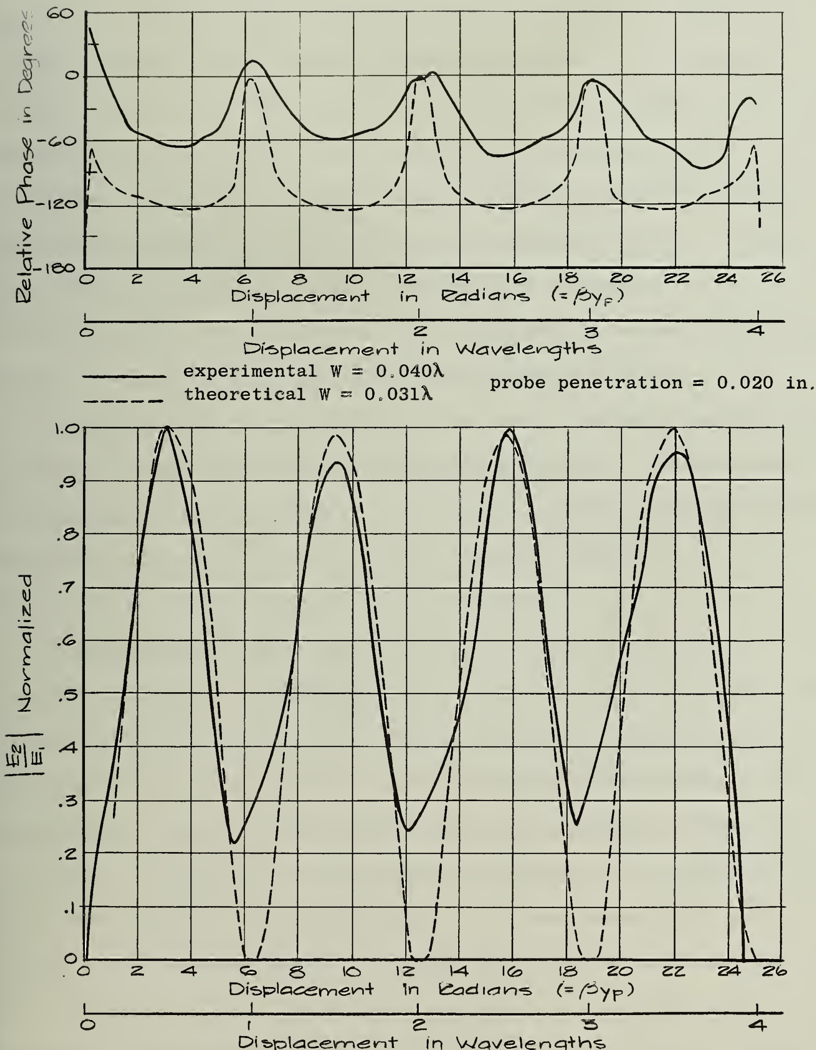


FIGURE 22 PHASE AND AMPLITUDE DISTRIBUTION OF A FOUR WAVELENGTH SLOT

decrease to zero amplitude. Since the theoretical curves are known to be least accurate in the regions of very low amplitude, the field might very well not be zero except at the ends of the slot. A number of experimental errors, however, can be used to explain some of this reluctance. The probe is of finite size and cannot, therefore, measure only over the infinitesimal distance where the minimum occurs. Although edge effects are suppressed, they probably do have an effect in the regions of lower amplitude, thus disturbing the pattern. The noise figures of equipment also limit the minimum measurable signal.

The experimental amplitude patterns are seen to closely resemble the theoretical amplitude patterns of a slightly longer slot. This lag might be explained, at least partially, by the greater height of the experimental aperture, similar to the effect of the increasing diameter of a dipole antenna causing a shorter effective length.[5]

The theoretical phase pattern of the 3.875λ slot in Fig. 21 is drawn with a number of discontinuities. The reason for the discontinuities is that the phase changes rapidly between successive calculated points. Thus some of the calculated points are not shown on lines because it is ambiguous as to whether these points lead or lag adjoining segments of the curve. It should also be mentioned that because of the low amplitude level the theoretical results are known to be least accurate in these regions. The indicated method of drawing the phase distribution seems to be the most continuous, although arguments can be exhibited which would make other methods of presenting the relationship between various segments of the curve just as plausible. It is seen by comparing the theoretical phase patterns of Figs. 20 and 22 that between an aperture

of 3.75λ and one of 4.00λ the trends in the phase pattern seem continuous except for a change in sign. This indicates a rapid shift and thus might explain the ambiguity in the phase pattern of Fig. 21. If a dipole of finite thickness[5] is again used as an analogy, a similar rapid shift in the sign of the input reactance takes place at approximately this same length, which corresponds to a resonance of the dipole.

Since experimental amplitude patterns correspond to slightly longer theoretical patterns, one might expect to find the same trend in the phase patterns. The fact that the discontinuities of the experimental phase pattern in Fig. 19 are similar to those of Fig. 21 help verify the expectation. The low signal levels and finite probe size make accurate phase measurement impossible in the regions of rapidly changing phase of the 3.625λ slot.

Because the apparent phase shift occurs at about 3.625λ for the experimental case and at about 3.875λ for the theoretical case, it is expected that experimental and theoretical phase patterns of a 3.75λ slot follow opposite trends. An inspection of Fig. 20 indicates that this is true.

5. CONCLUSIONS

This work has shown that the reaction concept is valuable in calculating approximately the field distribution in long, narrow, rectangular slots. The calculated distributions closely approximate the measured distributions where the amplitude of the field is large. At the places where the field amplitude is small, both the theoretical and experimental values are the least accurate and close agreement can not be expected at these points.

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